INTRODUCTION

For the past few years, the National Renewable Energy Laboratory (NREL) has managed a series of light-duty vehicle chassis dynamometer emissions tests on alternative fuel vehicles (AFVs) for the U.S. Department of Energy (DOE). These tests are part of a larger program to demonstrate the use of AFVs that was mandated by the Alternative Motor Fuels Act of 1988 (AMFA) and the Energy Policy Act of 1992 (EPAct). One of the major objectives of these legislative actions is to promote the use of alternative transportation fuels in order to address energy security and environmental issues. As part of the AMFA program, vehicle performance, operational costs, maintenance, and fuel economy data are also being collected by NREL's Alternative Fuels Utilization Program and disseminated through the Alternative Fuels Data Center (AFDC). This report is designed to present a detailed evaluation of the emissions test results collected in this program.

The principal phase of the AMFA test program was initiated in 1994. Its purpose was to determine relative emissions from AFVs compared to otherwise identical gasoline vehicles taken from actual service. Approximately 25 each of several AFV models from several locations (including high altitude) around the country were randomly selected for participation in this program. All vehicles were selected from those available in the U.S. federal fleet. Test vehicles were scheduled for emissions testing once per year. The test matrix of vehicles, locations, and mileage levels was statistically designed to optimize reliability of the data and to control variability in the emissions results.

In addition to testing all vehicles for regulated exhaust and evaporative emissions, we conducted a detailed speciation of the hydrocarbon (HC) emissions on a subset of the test vehicles. Speciation of the HC emissions allows for an evaluation of the relative level of air toxic emissions and the reactivity or ozone forming potential (OFP) of the HC. Additionally, we also tested a small number of vehicles using new or proposed chassis dynamometer driving cycles. These "off-cycle" emissions tests are still in progress and the results will be discussed in a later report.

A BACKGROUND ON VEHICLE EMISSIONS AND FUEL ECONOMY

As a result of fuel combustion, automobiles emit various compounds into the atmosphere in the form of exhaust. The U.S. Environmental Protection Agency (EPA) regulates some of these compounds; the amounts of the compounds that are emitted by vehicles cannot exceed certain levels. Other compounds, although not officially regulated, are important contributors to adverse atmospheric conditions such as ambient ozone and global climate change.

The emissions compounds regulated by the EPA include carbon monoxide (CO), oxides of nitrogen (NO_X), HC, and non-methane hydrocarbons (NMHC). Methane (CH_4) is not currently regulated because it is considered to be relatively non-reactive in forming ozone in the atmosphere. Exhaust from alcohol fuel vehicles also includes unburned alcohol and aldehydes, which are partial combustion products. For alcohol fuels, such as the ones investigated in this study, these compounds are regulated along with non-methane hydrocarbons as non-methane hydrocarbon equivalent (NMHCE). NMHCE is calculated by modifying the measured NMHC fraction to account for the alcohol and aldehyde emissions that are prevalent in emissions from alcohol fuels. More recent standards use non-methane organic gases (NMOG) as the regulated compound. NMOG is the sum of non-oxygenated and oxygenated HC in a gas sample. This includes all oxygenated organic gases with 5 or less carbon atoms (such as aldehydes, ketones, and alcohols) and all known alkanes, alkynes, alkenes, and aromatics with 12 or less carbon atoms.[3] The EPA's emissions standards applicable to the light-duty vehicles tested in this program are given in Table 1. Table 2 shows the EPA standards applicable to the heavy light-duty vehicles that were tested. EPA defines heavy light-duty vehicles as those with gross vehicular weight ratings between 6,000 and 8,500 lb.

Hydrocarbons can also escape from a vehicle through evaporation of the liquid fuel. Such evaporation occurs in several ways. Diurnal evaporative losses are emissions that occur during the day as the temperature rises.

Table 1. Intermediate Useful Life (5 years, 50,000 miles) Standards for Light-Duty Vehicles (g/mi)[4]

Fuel	Standard	THC	NMHC	NMOG	HCE	NMHCE	CO	NOx
Gasoline	Tier 0	0.41					3.4	1.0
Gasoline	Tier 1	0.41	0.25				3.4	0.4
Alcohol	Tier 0				0.41		3.4	1.0
Alcohol	Tier 1				0.41	0.25	3.4	0.4
	TLEV			0.125			3.4	0.4

Table 2. Intermediate Useful Life Standards for Heavy Light-Duty Vehicles (g/mi)[4]

Standard	THC	NMHC	CO	NOx
Tier 0 (120,000 mi full useful life)	0.80	0.67	10	1.7
Tier 1 (5-yr or 50,000 mi intermediate useful life)		0.32	4.4	0.7
Tier 1 (100,000 mi intermediate useful life)		0.4	5.5	0.97

As the fuel tank temperature increases, fuel evaporation increases and vapors are vented. Hot soak losses occur after the vehicle is turned off—the engine and fuel tank remains hot for a period of time, allowing further fuel evaporation. While the vehicle is running, the hot engine and exhaust system cause additional fuel to be vaporized. These emissions are called running loss emissions. Finally, during refueling, fuel vapors present in the tank are forced out as the tank is filled, resulting in refueling losses.[5] Since this test program began, the EPA has expanded its Federal Test Procedures for evaporative emissions to include procedures for each of the evaporative sources listed above. However, all the evaporative emissions results discussed in this report are from the previous EPA test procedures that were limited to two (one diurnal and one hot soak) 1-hour evaporative emissions tests.

Modern light-duty vehicles include evaporative control systems that contain and redirect much of the vaporized fuel back into the engine. One notable exception is compressed natural gas (CNG) vehicles. For vehicles designed to operate exclusively on CNG, the fuel remains in a gaseous state, and the entire fuel system is sealed under pressure. Therefore, a separate evaporative control system is not necessary for these vehicle types.

The non-regulated emissions evaluated in this study include carbon dioxide (CO_2), CH_4, and air toxics. CO_2 and CH_4 are greenhouse gases that trap the earth's heat and may contribute to global warming. Air toxics are pollutants that EPA classifies as known or probable human carcinogens—in other words, components considered to have adverse affects on human health. The air toxics evaluated in this study include benzene (C_6H_6), formaldehyde (HCHO), acetaldehyde (CH_3CHO), and 1,3-butadiene (C_4H_6). Benzene is a known carcinogen, and the latter three compounds are probable carcinogens.

Hydrocarbon emissions from vehicles may be made up of hundreds of individual hydrocarbon compounds or species. A gas chromatograph can be used to quantify the amounts of the individual HC species in a process known as detailed HC speciation. In this report, the speciation of hydrocarbon emissions is used to gain additional insight into HC emissions. Air toxics emissions are reported directly and as potency-weighted toxics (PWT). Potency weighting gives an indication of the relative level of risk for each of the toxic compounds emitted. The EPA has calculated an inhalation unit risk factor for each of the hazardous compounds. The weighting factor for each compound is determined by dividing its individual unit risk factor by the unit risk factor that is the highest of the four (in this case, 1,3-butadiene). The resulting number is multiplied by the mass emissions for the respective compound to calculate the PWT value. For example, acetaldehyde has a risk factor that is 127 times lower than 1,3-butadiene. The total PWT is the sum of the individual potency weighted values. These EPA risk factors are listed in Table 3.[6]

Results from the HC speciation are also used to evaluate the tendency for HC emissions to react in the atmosphere and form ozone. These results are reported here as OFP and specific reactivity (SR). Regulations in California assign a maximum incremental reactivity (MIR) value to individual compounds emitted in automobile exhaust. The MIR value is the predicted contribution of the compound to ozone formation in certain urban atmospheres, and is expressed in units of milligrams of ozone formed per milligram of the compound emitted. The MIR value is determined in a laboratory experiment in which a small increment of the compound is added to a simulated urban background mixture and the net increase in ozone is measured. Taking into account the MIR values for all measured exhaust compounds, an OFP for the fuel in question may be calculated. Specific reactivity for a given fuel may also be calculated by combining the respective mass of compound emissions per mile with the OFP, which results in units of milligrams of ozone per milligram of total organic emissions. In California, SR is based on NMOG emissions. Specific reactivity is usually constant for a given fuel and engine technology. To clarify the difference between them, OFP gives an estimate of the amount of ozone formed per mile traveled; SR gives an estimate of the amount of ozone formed per gram of NMOG emitted. OFP and SR are relative numbers associated with particular atmospheric conditions.

Fuel economy is also calculated from the results of the emissions testing procedures. For vehicles tested on gasoline, fuel economy is reported in miles per gallon (mpg). For vehicles tested on alcohol fuels, fuel economy is expressed both as miles per gallon and miles per equivalent gallon (mpeg). The mpeg measurement gives an estimate of how far the vehicle can travel on an amount of fuel that has the same energy as a gallon of gasoline. Both are reported for alcohol tests because alcohol fuels have a lower volumetric energy content than gasoline. The energy content of the methanol test fuel (M85) is approximately 58% of gasoline; the energy content of the ethanol test fuel (E85) is approximately 73% of gasoline (M85 and E85 are further described below). For vehicles tested on CNG, fuel economy is reported only in miles per equivalent gallons.

Table 3. EPA Unit Risk Factors for Emissions Air Toxics

Compound	EPA Risk $(\mu g/m3)^{-1}$	EPA Factor (Normalized)
1,3-butadiene	2.8×10^{-4}	1.000
Benzene	8.3×10^{-6}	0.030
Formaldehyde	1.3×10^{-5}	0.046
Acetaldehyde	2.2×10^{-6}	0.008

This is used for CNG tests because CNG is stored in a compressed gaseous state, which is not typically measured in gallons. For transportation applications, CNG is often dispensed and priced per gasoline gallon equivalent.

Test Vehicles for the Study

This report presents emissions test results on a number of different vehicle models. Table 4 lists these vehicle models, along with the numbers of vehicles of each model that were tested, and the total numbers of tests that were performed on all vehicles of each model. For every AFV model tested, an equivalent number of vehicles of the corresponding standard gasoline model (controls) were also tested. Because many vehicles were tested more than once over the course of the program (at increased mileage levels) more tests than vehicles are reported in Table 4. Replicate tests were also conducted on some vehicles. All the vehicles discussed here are original equipment manufacturer (OEM) vehicles. The test vehicles include four passenger car models, one full-size passenger van, and one minivan.

In order to provide information on emissions deterioration over time, the vehicles were scheduled for testing approximately once per year. The first set of tests on a particular vehicle model was designated as "Round 1," the second set as "Round 2," and so forth.

Both alcohol-fueled and CNG-fueled AFVs were included in the testing program. The principal alcohol fuels of interest were M85 (a blend of 85% methanol and 15% gasoline) and E85 (a blend of 85% ethanol and 15% gasoline). The alcohol-fueled vehicles are flexible-fuel vehicles (FFVs), which means that they are capable of operating on unleaded gasoline, or any blend of the alcohol and gasoline up to 85% alcohol and 15% gasoline. All the CNG models included in this report are dedicated CNG vehicles, which means they are designed to operate on CNG only.

As noted above, all test vehicles included in this program were part of the federal vehicle pool leased to various government fleets by the General Services Administration (GSA). A relatively large number of vehicles were selected for testing to account for the high variability observed in emissions from vehicles pulled directly from fleet service. These differences may be caused by physical differences inherent in any manufacturing process, or because vehicle usage and care vary from driver to driver and fleet manager to fleet manager. For instance, vehicle service applications may vary from short delivery routes to highway driving, and the degree to which the preventive maintenance schedule is followed depends, to a certain extent, on the diligence of the fleet manager. For these and other reasons, vehicle-to-vehicle variability in emissions levels was expected to be fairly high, even at the outset of the testing program.

Table 4. Emissions Tests Completed

Vehicle Model	Model Year	Vehicle Type	Number of Vehicles Tested	Number of Tests
Methanol				
Dodge Intrepid	1995	M85 FFV	24	89
		Standard	25	47
Dodge Spirit	1993	M85 FFV	77	373
		Standard	72	145
Ethanol				
Ford Taurus	1994/95	E85 FV	24	88
	1995	Standard	24	45
Chevrolet Lumina	1992/93	E85 FFV	25	144
	1993	Standard	16	45
Compressed Natural Gas				
Dodge B-250	1992/94	Dedicated CNG	54	144
		Standard	53	138
Dodge Caravan	1994	Dedicated CNG	13	16
		Standard	6	6
Total			413	1,280

Test Facilities

All testing was performed at private commercial laboratories with chassis dynamometer exhaust and evaporative emission test equipment that is capable of performing EPA emissions certification test procedures. A detailed description of the type of test procedures and equipment used can be found on the AFDC Web site (http://www.afdc. doe.gov). The laboratories were selected on the basis of a federal government competitive bidding process in which experience with performing the Federal Test Procedures (FTP)—in particular, FTP testing of alcohol and natural gas vehicles—was stressed. Three organizations were awarded emissions testing subcontracts: Automotive Testing Laboratories (ATL) in East Liberty, Ohio, which tested vehicles from Ohio, Michigan, and Illinois; Environmental Research and Development (ERD), which tested vehicles in the Washington D.C. and New York City regions; and ManTech Environmental Technology, Inc. (ManTech), which tested vehicles from Colorado (at a high altitude of approximately 5,300 feet). For the remainder of the report, these labs are referred to as Lab 1, Lab 2, and Lab 3, respectively. Before any testing began, a coordination meeting was held between all the participating laboratories and NREL to ensure consistency in the test procedures. NREL and EPA employees subsequently conducted laboratory site visits.

Test Fuels

Table 5 summarizes the physical properties of the liquid test fuels used in this study. The baseline gasoline used was California Phase 2 reformulated gasoline, or RFG. This fuel was chosen because it represents a "best case" scenario for gasoline emissions. If alternative fuels are to compete, they must be compared to the best gasoline available. RFG has a lower sulfur, olefin, and aromatic content than standard unleaded gasoline. The Auto/Oil Air Quality Improvement Research Program (AQIRP) conducted extensive testing that compared emissions from vehicles tested on various fuel blends, including certification test fuel, industry-average gasoline, and RFG[2]. In general, the AQIRP study found that vehicles tested on RFG tended to show reduced regulated emissions. Therefore, one might expect that the comparison between alternative fuels and an industry-average gasoline would be slightly more favorable for alternative fuels than the results discussed here. The alcohol blends were prepared using 85% alcohol (methanol or ethanol) and 15% RFG. Phillips Petroleum Company blended and supplied the alcohol and gasoline fuels. Compressed Gas Technologies, Inc., supplied the CNG fuel that was designed to represent a national industry-average fuel composition.

Table 5. Liquid Fuel Properties

	M85	E85	RFG
Fuel Blend	**85% Methanol 15% RFG**	**85% Ethanol 15% RFG**	**100% RFG**
Specific Gravity	0.787	0.784	0.741
Carbon (wt %)	44.1	56.7	84.4
Hydrogen (wt %)	12.7	13.2	13.6
Oxygen (wt %)	43.1	30.1	2.0
Net Heat of Combustion (Btu/gal)	64,600	81,825	111,960
Reid Vapor Pressure	7.5	6.15	6.9

Table 6 lists the specifications and a sample analysis of the CNG fuel used throughout the study.

Table 6. Composition of CNG

	% Volume	
Component	**Specification**	**Analysis**
Methane	93.05	93.15
Ethane	3.47	3.52
Nitrogen	1.67	1.47
Carbon Dioxide	0.81	0.82
Propane	0.66	0.68
N-Butane	0.12	0.13
I-Butane	0.08	0.07
N-Hexane	0.06	0.06
I-Pentane	0.04	0.06
N-Pentane	0.03	0.04
Oxygen	0.00	0.00

Test Procedures

This program used the EPA's emissions certification test procedure, known as the FTP-75. The FTP-75 includes measurement of exhaust emissions on a chassis dynamometer and two 1-hour evaporative emissions tests. Details of the test procedures are described in the *Code of Federal Regulations*[4]. Once a vehicle was identified for testing, the laboratory notified the fleet representative and scheduled a convenient test date. The lab also verified that the vehicle had received all scheduled maintenance and was operating properly. On arrival at the test laboratory, the vehicle was inspected for any problems. Once the vehicle was approved for testing, it was subjected to an extensive procedure designed to minimize residual effects from resident fuels. Figure 1 outlines the complete procedure for testing a vehicle, including the fuel changeover procedure. The fuel changeover procedure was performed before every test, including the first test in the sequence. This process follows the AQIRP's vehicle testing procedures.[7] The main elements of the fuel changeover procedure are a 60-minute purge of the vehicle's evaporative canister, several fuel tank drain and fill sequences, a chassis dynamometer driving cycle using the test fuel, and several engine start-up and idle sequences. Another part of the vehicle preconditioning procedure is the Urban Dynamometer Driving Schedule (UDDS), also called the LA4. The UDDS was derived from an actual driving route through LA that was selected to represent a typical city driving pattern.

Once the fuel changeover procedure was complete, the vehicle was tested following the FTP-75 for light-duty vehicle chassis dynamometer testing (including evaporative testing). Figure 2 shows the FTP-75 driving cycle. Alcohol fuel vehicles were tested on both alcohol fuel (M85 or E85) and RFG. The corresponding control vehicles were tested on RFG. All CNG vehicles were tested only on CNG fuel, and their corresponding gasoline controls were tested on RFG.

The emissions samples collected during the FTP were analyzed for HC, CH_4, NO_x, CO, and CO_2. Alcohols (ethanol and methanol) in the emissions were collected using primary and secondary impingers. Gas chromatography was used to analyze the alcohols. Aldehydes were collected on dinitrophenylhydrazine (DNPH) coated silica cartridges or impingers filled with an acetonitrile/DNPH solution, and analyzed

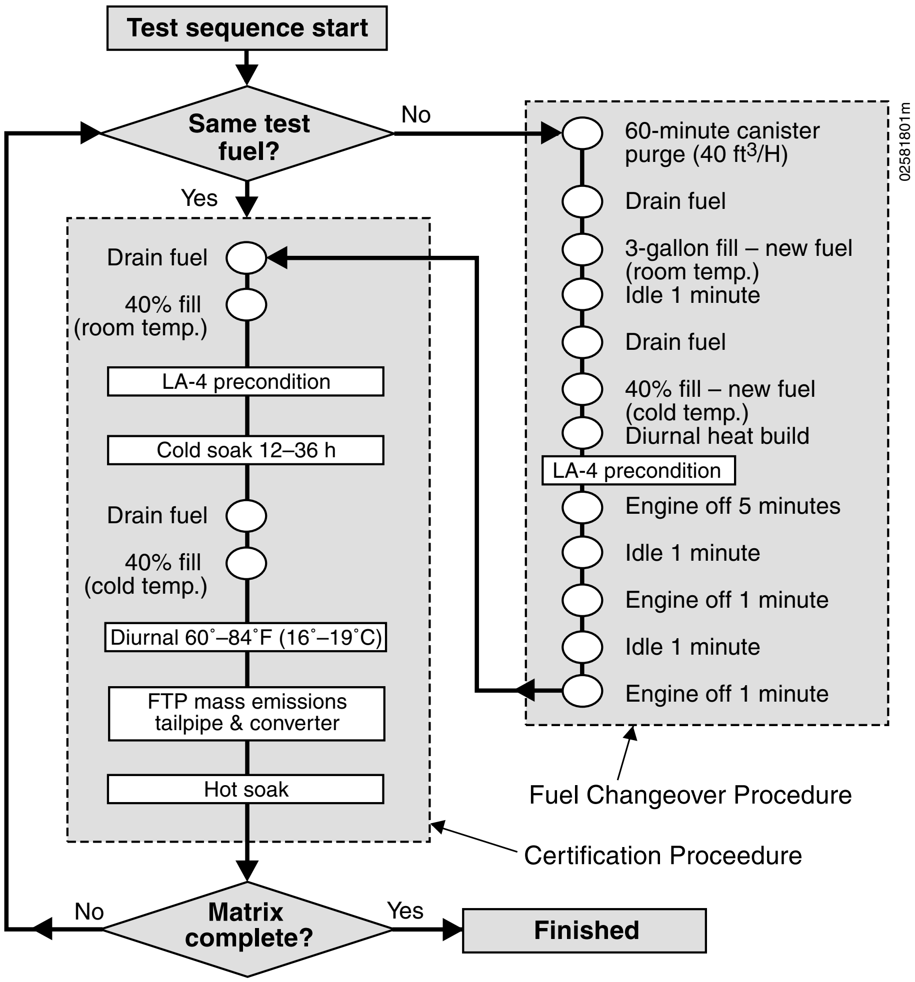

Figure 1. Vehicle testing procedure

using high-performance liquid chromatography. Appendix A contains the entire FTP data set.

The emissions from a subset of test vehicles were subjected to full hydrocarbon speciation. Speciation is the quantification of individual HC components using gas chromatography. Table 7 lists the numbers and types of vehicles for which hydrocarbon emissions were speciated. Up to 288 HC constituents in the emissions samples were identified; a complete list is given in Appendix B. Appendix C contains the speciated HC data set.

Data Analysis Approach

Raw data files of the emissions tests from each laboratory were electronically submitted and loaded into the AFDC at NREL. Before conducting any analyses of the data, a number of checks and edits were undertaken to ensure data quality. The data sets were sorted by vehicle model, test fuel, and test round. Repeat tests were reviewed for problems or outliers. In most cases, these duplicate tests were averaged and returned to the data set. Each data set was then analyzed for outliers, which were removed. Outliers were defined as any value that was +/- 3 standard deviations from the mean. An exception was made with the evaporative emissions results. Because of the high variability of evaporative data, no outliers were removed from the data sets.

After all checks and edits were applied, the data were imported into the JMP® software, which is a comprehensive PC-based statistical data analysis package developed by SAS Institute. Using this software, a multi-variable analysis of variance (ANOVA) was performed to determine the statistical significance of various factors on emissions. The primary effects of interest include fuel, vehicle, and test round. Secondary effects include the fuel by vehicle, fuel by test round, and vehicle by test round interactions. All data were analyzed at the 95% confidence level. Appendix D gives a detailed explanation of the data compilation and the ANOVA statistical approach.

Presentation of Analysis Results

The following sections contain discussions of the results from each of the individual vehicle models tested. Sections on each alternative fuel begin with an overview comparing the fuel with RFG, followed by details on each model. The discussions on each vehicle model are subdivided into sections on regulated emissions, evaporative emissions, greenhouse gases, and aldehydes. Separate tables and graphs cover the air toxics, OFP, and SR. Each of these sections concentrates on the comparison between the emissions and the EPA standard, fuel differences, and round-to-round differences.

The results are presented in tables that include regulated and non-regulated emissions constituents for each vehicle model. These tables contain descriptive statistics for emissions results obtained for each fuel on which the vehicle model was tested. Average emissions are reported as grams per mile. Of particular interest is the percent difference between the emissions from the alternative fuel and the RFG tests (e.g., M85 versus RFG).

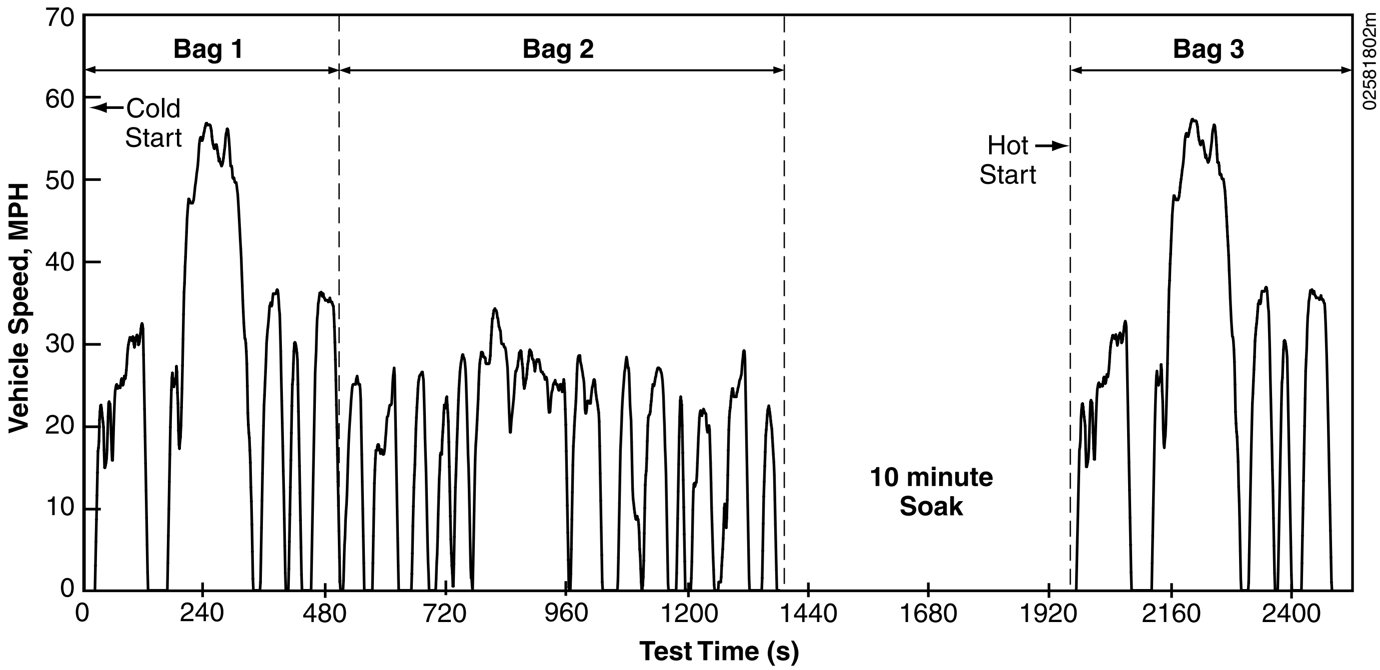

Figure 2. EPA's FTP-75 driving cycle

For each vehicle model tested, a summary table of results shows the average results, percent differences between the averages, and an indication of which differences in average values are statistically significant at the 95% confidence level. Percent difference was calculated using the following formula:

$$\frac{\overline{U}_{AlternateFuel} - \overline{U}_{Gasoline}}{\overline{U}_{Gasoline}} \text{ x } 100,$$

where $\overline{U}$ is the average of emissions test results obtained on the fuel in question. Statistical significance was determined through ANOVA procedures, applying the appropriate data model for each particular case. An example ANOVA table is shown in Appendix D.

In addition to the tables, each section contains a series of graphs depicting the average emissions results (by fuel, lab, and/or round) for the different fuels tested. Bar charts or line graphs are used to illustrate the differences between fuels. The text accompanying the tables and graphs describes the various trends depicted in them, and discusses the statistical significance (if any) of those trends.

For the alcohol-fuel vehicle models, the comparisons discussed concentrate on the difference between the alcohol and the gasoline tests on the FFV. This eliminates any discrepancies in the results that could result from large differences in odometer readings for the FFV and gasoline control vehicles. The results for the gasoline control model are shown in the graphs for reference. Because the CNG vehicles are dedicated vehicles, the comparison must be made between the AFV and the gasoline control. Odometer range differences between these vehicles could play a part in the test results.

Table 7. Number and Type of Vehicles with HC Speciation

Model	Fuel	Type	Number of Vehicles	Number of Tests
Dodge Intrepid	M85	FFV	6	16
	RFG	Standard	4	7
Dodge Spirit	M85	FFV	10	28
	RFG	Standard	9	14
Ford Taurus	E85	FFV	6	16
	RFG	Standard	5	8
Dodge B250	CNG	Dedicated CNG	8	17
	RFG	Standard	8	16
Total			56	122